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A review of biomass burning emissions part II: intensive physical properties of biomass burning particles

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Abstract. The last decade has seen tremendous advances in atmospheric aerosol particle research that is often performed in the context of climate and global change science. Biomass burning, one of the largest sources of accumulation mode particles globally, has been closely studied for its radiative, geochemical, and dynamic impacts. These studies have taken many forms including laboratory burns, in situ experiments, remote sensing, and modeling. While the differing perspectives of these studies have ultimately improved our qualitative understanding of biomass-burning issues, the varied nature of the work make inter-comparisons and resolutions of some specific issues difficult. In short, the literature base has become a milieu of small pieces of the biomass-burning puzzle. This manuscript, the second part of four, examines the properties of biomass-burning particle emissions. Here we review and discuss the literature concerning the measurement of smoke particle size, chemistry, thermodynamic properties, and emission factors. Where appropriate, critiques of measurement techniques are presented. We show that very large differences in measured particle properties have appeared in the literature, in particular with regards to particle carbon budgets. We investigate emissions uncertainties using scale analyses, which shows that while emission factors for grass and brush are relatively well known, very large uncertainties still exist in emission factors of boreal, temperate and some tropical forests. Based on an uncertainty analysis of the community data set of biomass burning measurements, we present simplified models for particle size and emission factors. We close this review paper with a discussion of the community experimental data, point to lapses in the data set, and prioritize future research topics.

1 Introduction

To understand the effects of biomass burning on the atmosphere, it is imperative that consistent parameterizations with reliable uncertainties be provided to models. In the last decade, biomass-burning studies have spawned hundreds of manuscripts on the physical, chemical, and thermodynamic properties of biomass-burning particles. Qualitatively, smoke particle properties are well understood. For example, approximately 80–90% of their volume is in the accumulation mode (d_p<1 μm). Smoke particles are composed of ∼50–60% organic carbon and ∼5–10% black carbon. Biomass smoke particles effectively scatter and absorb solar radiation. Given sufficient updraft velocity, smoke particles are good cloud condensation nuclei. But despite this qualitative understanding, the determination of key parameters for estimating atmospheric effects of biomass burning is not straightforward. Smoke properties vary between fires depending on fuel type and moisture, combustion phase, wind conditions, and several other variables. Also, as the physical, chemical, and optical properties of biomass-burning aerosols can change rapidly as they disperse, it is difficult to relate the properties of individual fires to the ensemble smoky hazes that affect the atmosphere's radiative balance. Determining the impacts of these hazes on the meteorology of a region is hampered by high uncertainty in both the measurement methodologies and in the models themselves. A key issue is the extent to which measurements presented in the literature can be applied to models of aged smoke that dominates regional hazes and affects seasonal climate. Ignoring the intricacies of this problem can result in very large errors in regional and global climate models.

This review paper is the second of four discussing biomass-burning emissions and their physical, chemical and optical properties. The intent of this series is to present to the scientific community the state of the field, and the true uncertainties in open biomass burning (e.g., excluding cooking, charcoal production, or industrial emissions). In this manuscript we review the literature regarding intensive physical properties and emission factors and of biomass-burning particles. By intensive we mean those that describe the inherent properties of the aerosol particles themselves, such as size or chemical mass fraction, rather than extensive properties such as concentrations or total mass flux. We explore differences in particle properties by region and fire chemistry, and attempt to reconcile differences that exist between measurement techniques and field studies. In conclusion, we present what we feel are reasonable smoke models with reliable uncertainties, and make suggestions for future research.

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8 Discussion, summary, and recommendations for future work

In this manuscript we gave an overview of the intensive physical and chemical properties of smoke particles from biomass burning. We focused on the commonly studied fuels such a grass/savanna, cerrado/brush forest, tropical forest and temperate forest. Although there is a tremendous body of literature on the subject of biomass-burning particles and some agreement on key issues, there are some obvious biases. Here we provide a summary and discuss the state-of-the-science. Where appropriate, present first order models are presented. We close each section with a discussion of outstanding issues.

8.1 Particle emission

Examination of Table 6 shows that while emission factors for grass and cerrado/shrub fuels are relatively well known, uncertainties dramatically increase for more forested biomes. These are likely due to a combination of sampling bias, instrumentation issues, and low statistical power (e.g., sample size). Grass and shrub fires are smaller in size and intensity, and are mostly consumed by flaming combustion. These aspects make such fires easier to characterize. Forested fires pose far more difficult challenges. Clearly, the high particle concentrations and temperatures make close analytical studies of these fires difficult and potentially dangerous. Since the heat source is so much larger than grass fires, modeling the impact of fire dynamics and intensity on particle properties is complex and non-linear. Long burn times, on the order of days for smoldering combustion to complete, makes monitoring the complete lifecycle and derivation of a "mean" emission factor logistically difficult for a forest fire. Additionally, we need to account for rapid particle condensation near the fire source.

Here we present a first order model for particle emissions. Net emission fluxes are most often determined by applying emission factors to estimates of land area burned, fuel loading, carbon fraction of the fuel, and combustion fraction. Following Seiler and Crutzen (1980) to derive the total flux of species (n) by summing over each vegetation/biome type (i):

$$Net\ Flux = \sum_i m_{fi} \cdot f_{ci} \cdot c_{fi} \cdot \langle EF \rangle_{ni} \cdot \left(\frac{A_i}{T_i} \right) \qquad (2)$$

where m_{fi} is the amount of fuel mass available for combustion in kilograms per square meter, f_{ci} is the average mass fraction of carbon in the fuel, c_{fi} is the combustion factor, A_i is the total area burned, T_i is the average time between burns, and here $<EF>_{ni}$ is the average emission factor for particles.

In Table 7 we present recommended emission factors and an uncertainty analysis of the factors required to forward model particle emissions. Because of the huge uncertainties in burn areas and fuel loads, we present data normalized as emissions per square meter burned, and assume some reasonable average fuel load for comparison purposes only from the values given above (i.e., not included in the uncertainty calculation). We recommend values for emission factors that are slightly higher than those in previous review papers that average the bulk of available emission factor data in the literature (such as Andreae and Merlet, 2003). We hypothesize that due to various sample bias issues, such an average would underestimate emissions on the order of 10 to 30%. First, one must consider issues of particle mass growth due to organic condensation during the first 30 min of smoke aging (we exclude other heterogeneous mass growth such as organic acid formation as this is heavily dependent on environmental variables this should be accounted for in models). This mass increase is not accounted for in fire tower measurements, nor even in many aircraft derived values. Similarly, combustion chamber studies are also likely to underestimate some emissions for forested type fuels. This correction would be greater for flaming combustion, and can be taken into account directly in the emission factors (which we have done).

The second issue is the lack of data on the relative amounts of flaming versus smoldering combustion. Even for savanna type fires, smoldering combustion on stumps and large wood debris can go on for hours or even days (D. Ward personal communication). While the mass flux is relatively slow, the long duration may make this a term that should not be neglected. For fires in forested ecosystems, smoldering is even more significant. This correction results in another 5–15% increase in the average emission factor.

The bulk of the uncertainty in normalized net emissions calculations still lies with the average emission factor, which we estimate to be ∼18% for grassy fuels (which show very consistent results in the literature), to mid values of 37% and a high of 40% for tropical forests (for which relatively few measurements are made). The higher mean uncertainties for emission factors from forest type fuels are not unexpected given the difficulty in characterizing large fires. For example, grass fires burn typically in the flaming phase and can be easily characterized by fire towers. Larger forest fires, however, have significant smoldering phases that can last for days (increasing uncertainty to that of the flaming plus smoldering phase). Large fires also vary considerably from event to event causing more spread in the community data set.

[1]Koppmann, R., von Czapiewski, K., and Reid, J. S.: A review of biomass burning emissions part I: Gaseous emissions and chemistry, Atmos. Chem. Phys. Discuss., in preparation, 2005.